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Turbule Ensemble Model of Atmospheric Turbulence: Progress in its Development and Use in Acoustical-Scattering Investigations

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Abstract

The objective of one portion of the Army Research Laboratory program on acoustic propagation on the battlefield is to develop an advanced method of accounting for the effects of anisotropic inhomogeneous turbulence. The approach chosen was to extend the idea of eddies under the assumption that the turbulence field is made up of a multiplicity of isolated eddies of different sizes. This method of describing turbulence is called the Turbule Ensemble Model (TEM). A turbule is defined to be a localized inhomogeneity of any type. The primary types are temperature and velocity inhomogeneities; the term turbule is an extension of the idea of an eddy, which is normally associated with a velocity disturbance. In the TEM, then, the turbulent region is populated with a collection of turbules of different sizes and types with the locations of the turbules chosen according to some rule. Since the program began in 1992, a number of publications have been generated that have dealt with the details of creating and using the TEM concept. This report contains information on these reports including author, title, where copies may be obtained, date, and a brief description.

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1. Introduction

The detection of sound on the battlefield has been exploited for various purposes throughout history. Current understanding of the atmosphere and its influence on acoustic propagation has improved the ability to predict detectability. One example is the ability to detect signals in regions where sound would not directly penetrate such as behind a large hill. These regions are termed shadow zones and their presence is not limited to the geometrical case just cited but can be formed when sound speed gradients exist. It has been found that sound levels in shadow zones are much enhanced when atmospheric turbulence is present. The enhancement is attributed to scattering by the turbulence itself. Thus, the Army is greatly interested in exploiting this effect as a way to detect enemy activity when line-of-sight observation is not possible. A portion of the Army Research Laboratory (ARL) program in acoustics is concerned with developing an advanced theory of atmospheric scattering from turbulence. The method used in this program has been tailored to the scenario of interest to the Army, that is, a scenario near the ground where turbulence properties are not uniform. The approach taken has been to represent the turbulence as a collection of isolated inhomogeneities. Such inhomogeneities have been called turbules, which is a generic term that can be applied to inhomogeneities regardless of cause. The primary causes are temperature and velocity disturbances. One can speak of velocity turbules or of a turbule in general as a shortened expression for an isolated inhomogeneity. The term turbule is a generalization of the common term eddy, the latter normally being associated with a velocity disturbance. This representation of turbulence is termed the Turbule Ensemble Model (TEM). In the TEM, the turbulent region is populated with a collection of turbules of different sizes and types with the locations of the turbules chosen according to some rule.

A number of publications dealing with creating and using the TEM concept have been generated since the program began in 1992. This report contains references to these publications and a brief description of each. The items are numbered sequentially and are organized according to the principal subject of the publication under the headings listed below. A reference made to another item in a description is indicated by the number of the other item in a bracket, as, for example [23].

Section 2. Background

Section 3. Scattering From a Single Turbule

Section 4. Properties of Turbule Ensembles With Continuous Size-Class distributions

Section 5. Scattering From Discrete Size-Class Turbule Ensembles

Section 6. Scattering From Moving Ensembles

Section 7. Using Propagation Models With Turbule Ensembles

Section 8. Summary

See appendix for key to suggested sources.

2. Background

The items in this section are provided to tie the TEM into previous work on turbulence scattering and as such were not products of the project effort.

1. Tatarskii, V. I., *The effects of the turbulent atmosphere on wave propagation*, Keter, Jerusalem, 1971.

Tatarskii is the basic work in the field of wave propagation in the turbulent atmosphere. At a conceptual level, turbulence can be described as eddies that are formed as a consequence of the forces exerted by the fluid flowing in one direction and by the force exerted by the surface in the other direction. The energy contributed by the flowing fluid cascades through a series of eddy sizes starting at the largest size. The final sink for this heat flux is in small eddies through viscous dissipation. A number of universal relationships devolve from this eddy picture. For one example, consider a field of eddies divided into size classes, and assume that each eddy class can be assigned a velocity and a length scale (such as a diameter or radius) characteristic of the class. In a generalized form of dimensional analysis, a characteristic time would be the length scale divided by the velocity. A further assumption is that the energy supplied by the flow is a constant per unit mass of the fluid in the turbulent region. The kinetic energy per unit mass is proportional to the velocity squared. The energy flow rate out of a size class is the kinetic energy divided by the characteristic time. This number, assumed a constant, is then set equal to the velocity cubed divided by the length scale. The result of this simple exercise is the notion that the velocity ratio between size classes is equal to the cube root of the length scale ratio between size classes. Many investigations have shown the essential correctness of this result and other relationships that are associated with it. Therefore, the picture of atmospheric turbulence being made up of eddies of different size classes must be, in at least a first order sense, correct. In a number of instances in the items listed below, results are specialized to isotropic homogeneous turbulence and compared to the corresponding results in Tatarskii.

2. Bohren, C. F., and D. R. Huffman, *Absorption and Scattering of Light by Small Particles*, John Wiley and Sons, New York, 1983.

I have included a reference to a work on light scattering because the basic method of finding the scattered signal from a turbule ensemble is similar to that used in the past to calculate the optical scattering from aerosol distributions. The difference is mainly the wavelength so that the scattering volume in acoustic scattering is ill defined, and the possibility must be included for coherent summation. A number of ideas presented here may not be familiar to many and might be useful in the future. The genesis of TEM came from applying calculation methods for scattering from aerosol distributions to the eddy idea of the previous item [1].

3. McBride, Walton E., "A Scattering Center Based Numerical Simulation of Small Scale Atmospheric Turbulence," Ph.D. dissertation, The University of Mississippi, Oxford, MS, August 1989.*

A computer simulation of the effect of small-scale turbulence on atmospheric sound propagation over a complex impedance boundary is developed in this dissertation. The atmosphere is broken up into spherically symmetric eddies characterized by a Gaussian profile for the change from unity of the index of refraction. Born and Rytov approximation expressions for scattering are obtained and the two compared. The Rytov approximation is adopted, and a numerical simulation is accomplished for a number of realizations of the turbulent medium. The predictions of the standard deviations of the amplitude fluctuations, amplitude probability distributions, and structure functions are compared to experimental data. To the best of my knowledge, the term turbule is first introduced here.

4. Noble, John M., "Sound Field Fluctuations Due to Large Scale Wind-Driven Turbulence," Ph.D. dissertation, The University of Mississippi, Oxford, MS, December 1989.*

A large-scale wind-driven turbulence model is put forth to account for long-term (1 to 5 min) phase variations observed in outdoor sound-propagation experiments. The large-scale turbulence in the boundary layer is assumed to be elongated longitudinal vortex pairs roughly perpendicular to the mean wind direction. The parabolic equation is used to compute the pressure and phase at a receiver as the vortex pair traverses the propagation path with the mean wind speed. The model provides good results with the same trends and variations in the magnitudes of the phase observed experimentally.

3. Scattering From a Single Turbule

The scattering properties of individual turbules are presumed known in TEM. The items in this section cover this topic in a number of ways.

5. Goedecke, G. H., "Scattering of Acoustical Waves by a Spinning Atmospheric Turbule," New Mexico State University, Las Cruces, NM, CR-92-0001-2, September 1992, U. S. Army Atmospheric Sciences Laboratory, (A258783).**

This report develops the linearized wave equation from an amalgamation of the mass continuity equation, the Euler equation, the heat-flow equation, and the perfect gas law. The scattering amplitude and cross section are derived in the first Born approximation for a Gaussian envelop velocity distribution and a related density distribution. Conditions are given for the validity of the results.

6. Lopez, José, G. H. Goedecke, and Harry J. Auvermann, *An Acoustic Scattering Code*, U. S. Army Research Laboratory, ARL-TR-53, April 1993, White Sands Missile Range, NM (A265863).**

The Acoustic Scattering from Turbules (ASCT) code described in this report uses Mie theory to obtain the exact scattering properties of uniform spherical acoustical index of refraction inhomogeneities. The result is obtained as an infinite series of coefficients expressed in terms of spherical Bessel functions and Hankel functions. Because of the slight index of refraction variations in the atmosphere, quadruple precision is used in the calculations. Application of ASCT to distributions of turbule sizes is also included.

7. DeAntonio, Michael D., "An Exact Model for Linear Acoustical Scattering from Atmospheric Turbulence," Ph.D. dissertation, New Mexico State University, Las Cruces, NM, December 1993.*

DeAntonio addresses the issue of going beyond the Born approximation to obtain the scattering properties of temperature and velocity turbules. The linearized fluid equations (continuity, Euler, perfect gas law) are solved directly by insertion of an auxiliary field. The latter allows writing differential equations for acoustic velocity and density functions that have terms with no higher than the second-order space derivatives. The digitized Green's function approach is applied to obtain a numerical solution for scattering of an incident plane wave. Later, it was pointed out that a more accurate derivation of the basic equations would involve an isentropic change of state of the combined turbulence and acoustic fields rather than just the isentropic change of the acoustic field as used in this reference. This change which must be carried through the derivation, has been worked out but not reported.

8. Auvermann, H. J., *Analytic Expression for the Decay History of an Atmospheric Turbule*, U. S. Army Research Laboratory, ARL-TR-1315, October 1997, (A331085).**

Beginning with the incompressible Navier-Stokes equation in terms of fluid velocity, the curl operator is applied to obtain an equation in the vorticity from which the pressure is eliminated. For an isolated Gaussian velocity turbule (whose divergence is zero), the conductive derivative term is perpendicular to the vorticity so that forming the dot product with the vorticity eliminates this term. The resulting equation is in terms of the square of the vorticity otherwise known as the enstrophy. Applying Fourier and Laplace transform theory solves this equation. The vorticity/velocity time history is deduced from the enstrophy time history. The conductive derivative term of the enstrophy equation remains identically zero throughout.

9. Auvermann, H. J., "Acoustical scattering amplitudes of wavelet-like atmospheric temperature distributions," 140th meeting of the Acoustical Society of America, 3 to 8 December 2000, Newport Beach, CA, *J. Acoust. Soc. Am.* **108**, November 2000, (5), pt. 2, p 2650 [Abstract only].

TEM is much like wavelet theory in that self-similar functions are applied at successively smaller scales to obtain a representative model of the field of interest. Wavelet decomposition is anticipated to be useful in inferring turbulence distributions from experimental data. In one dimension, wavelets are defined to have a zero integral. This definition cannot in all cases be easily carried over into the three-dimensional realm of TEM. Reported here is the scattering amplitude for six candidates for wavelet series decomposition of a temperature turbulence field. The candidates are the Gaussian, exponential, "Mexican hat," morlet, cosine, and concentric spheres. Born theory is used for the first five, and the exact theory [6] is used for the last.

4. Properties of Turbule Ensembles With Continuous Size-Class Distributions

Basic theory for the properties of turbulence [1] assumes that the turbulence is mostly isotropic and homogeneous. Such theory features a continuous distribution of turbulence length scales in the energy cascade process from the largest features where energy is supplied to the smallest features where energy is dissipated. Although TEM was developed for the anisotropic inhomogeneous case, it can be particularized for the isotropic homogeneous case. As a test of the validity of TEM, one can compare properties inferred from it to the same properties developed over the years with the use of the standard methods [1]. The standard results have been validated against measured results in numerous experiments. Therefore, validity of standard results transfers to TEM results if the two match. Items in this section record this match-up.

10. Four papers presented at the 126th meeting of the Acoustical Society of America, Denver, CO, 4 to 8 October 1993, *J. Acoust. Soc. Am.* **94**, September 1993, (3), pt. 2. [Abstracts only].

"On statistical fluctuations in single scattering by an ensemble of scatterers," p 1774.

"Connection between structural and statistical models of atmospheric turbulence," p 1874.

"First-order acoustical wave equations and scattering by atmospheric turbulence and turbules," p 1776.

"Coupled wave equations for numerical calculation of acoustical propagation and scattering by atmospheric turbulence," p 1776.

These four papers presented the accumulated findings of the program up to the date of the meeting. The subjects of these papers are covered in more detail in other publications (first paper, see [19]; second paper, see [15]; third paper, see [14], fourth paper, see [9]).

11. Auvermann, H. J., G. H. Goedecke, and M. D. DeAntonio, "The influence of scattering volume on acoustic scattering by atmospheric turbulence," Proc. of the 1994 Battlefield Atmospherics Conference, 29 November to 1 December 1994, White Sands Missile Range, NM, (A378412).**

Building upon prior work [18,19], this paper presents the relationships used to ascertain the scattered signal at a detector including turbule cross section and number concentration for a plane wave incident upon the scattering volume. A portion of the scattering volume, a spherical shell, is further analyzed. The relative scattering volume as a function of turbule size is calculated showing how the turbule-scattering pattern limits the volume that must be considered. Validity of the results is discussed related to disregard

of surface integrals when very large turbules are present. The last three references in this paper were not published as shown. The information is contained in other reports (See [14–16]).

12. Auvermann, H. J., "Calculation of scattering volume limits for acoustical scattering from homogeneous turbulence using the turbule ensemble model," *Proc. 6th Annual Ground Target Modeling and Validation Conference*, August 1995, Michigan Technological University, Houghton, MI, pp 474–483, (proceedings: B205846, paper A378687).**

This paper answers the question, why does turbulence scattering seem to come from a definite volume of space although acoustic sources and detectors in the audio frequency range are nearly omnidirectional. The scattering properties of turbules are not omnidirectional if their dimensions are comparable to or larger than the wavelength being used. Large turbules scatter preferentially in the forward direction. This property is exploited to define a region (called the effective scattering volume (ESV)), which is different for different size-to-wavelength ratios, and for which a majority of scattering occurs. The calculation assumes a continuous distribution of turbule sizes and allows determination of the relative contribution of each size for a given geometry.

13. Auvermann, H. J., and G. H. Goedecke, "Shadow zone boundary limitation of the acoustical turbulence scattering volume using the turbule ensemble model," *Proc. of the 1995 Battlefield Atmospherics Conference*, 5 to 7 December 1995, White Sands Missile Range, NM. [In error, the paper was omitted from the proceedings]. Published as ARL-TR-2234, U. S. Army Research Laboratory, September 2000 (A383806).**

This paper is an extension of the above paper [12]. Calculation of the ESV includes a wind-induced shadow zone boundary that defines the turbule height below which scattered radiation cannot reach the detector. The result is that large turbule contribution is further reduced for source/detector combinations near the ground. The shadow zone boundary expression is deduced for ground-area coordinates assuming ray theory holds for a sound speed that declines with a constant altitude gradient.

14. Goedecke, G. H., M. DeAntonio, and H. J. Auvermann, "First-Order Acoustic Wave Equations and Scattering by Atmospheric Turbules," U. S. Army Research Laboratory, ARL-TR-1356, August 1997 (A328618).**

This report and the succeeding two items ([15,16]) cover in depth the findings of the investigation into the use of TEM as a turbulence model for acoustical scattering. The emphasis in this report is on the derivation of the acoustic wave equation and an examination of the order of magnitude of the various terms retained. General properties of isotropic ensembles (i. e., orientation averaged) are deduced. The concept of comparable turbules is introduced so that morphology comparisons can be made.

15. Goedecke, G. H., M. DeAntonio, and H. J. Auvermann, "Structure Function Spectra and Acoustic Scattering Due to Homogeneous Isotropic Atmospheric Turbule Ensembles," U. S. Army Research Laboratory, ARL-TR-1518, August 1998.**

As a member of the three-member group (including [14–16]), this report contains derivations of the spectral densities of temperature and velocity structure functions for TEM with turbules of arbitrary morphology. Shown are curves of these spectra that match the Kolmogorov spectrum obtained the conventional way [1] within the inertial range. Outside the inertial range, the spectra are morphology dependent (see [14]). Also shown are the conditions under which it is possible to measure the extra inertial range spectrum.

16. Goedecke, G. H. and H. J. Auvermann, "Acoustic scattering by atmospheric turbules," *J. Acoust. Soc. Am.* **102** (2), August 1997, pt. 1, pp 759–771.

As the remaining member of this group (with [14,15]), this journal article records with some redundancy those aspects of TEM use pertaining to acoustic scattering. Power law scaling properties of turbulence are shown to result from the requirement that the kinetic energy transfer be independent of turbule size and from the choice of fractal scaling. By matching the TEM spectra exponent to the Kolmogorov spectrum exponent, one can calculate the structure parameter in terms of TEM parameters. All the information is thus available to synthesize a turbule ensemble with properties that mimic a turbulence field whose structure parameters were obtained experimentally.

5. Scattering From Discrete Size-Class Turbule Ensembles

Numerical experiments were conducted with the use of examples of turbule distributions typical of field experiments that had been reported. These experiments accompanied the theoretical investigation of the similarity of TEM properties with those of standard theory as presented in the items listed in section 4. The pertinent findings of the field experiments were the extreme variability of the detected signal (some 200:1) and the broadening of a monochromatic source tone into an appreciable band of components. The method used in all but one of the numerical experiments was single scattering, meaning that the incident field was assumed to insonify all turbules and the scattered waves from each turbule were assumed to proceed to the detector unmodified by other turbules. The one example of a multiple scatter investigation is included in [17].

17. Rollins, C., D. Resendes, and M. R. Squillante, "Acoustic Scattering by a Vortex Model of Turbulence," Contract No. DAAL06-92-C-0006, Final Report, 19 November 1992, Radiation Monitoring Devices, 44 Hunt St., Watertown, MA, (A382467).**

This is the final report on a small business innovative research (SBIR) phase I contract. Budget shortfall prevented funding for the follow-on Phase II effort. The limited scope of this theoretical investigation nevertheless outlined a method possibly useful in a future analysis of experimental data. A self-consistent field approach adapted from previous electromagnetic investigations was applied to solve the multiple scattering problem in acoustics for a limited region in a turbulent field. Exactly how the regional boundary is to be handled is not specified in the report.

18. Auvermann, H. J., and G. H. Goedecke, "Acoustical scattering from atmospheric turbulence," *Proc. 1992 Battlefield Atmospherics Conference*, 1 to 3 December 1992, Ft. Bliss, TX, 1992, pp 43-52 (A377885).**

This paper describes the procedure for modeling acoustical scattering from turbulence when the turbulence is modeled as in TEM. Five steps are indicated as necessary. The first three are essentially those involved in setting up TEM (termed the structural approach in this paper). The fourth and fifth involve a propagation model and the summation of the scattering signal contribution from each turbule. The complete calculation is carried out with reasonable assumptions made for those quantities not known at the time. Use is made of the Acoustic Multistream Propagation Program (AMPP) computer model described below [31]. Some of the problems identified in this study changed the objectives of future research and others have yet to be solved.

19. Goedecke, G. H., M. DeAntonio, and H. J. Auvermann, "Fluctuations of acoustic signals scattered by an ensemble of turbules," *Proc. of the 1993 Battlefield Atmospherics Conference*, 30 November to 2 December., 1993, Las Cruces, NM, pp 105–115 (A377729).**

The highly variable nature of measured shadow-zone signals became known within the time frame of this report.¹ Theory in this paper shows that scattering from a structurally described turbulence volume is a possible mechanism for these fluctuations even though the number of scatterers is relatively large. A simple turbule ensemble was generated and the coherent summation of the signal scattered into a detector was compared to the measured signal as the ensemble flowed through the scattering volume. The turbule scattering pattern used was that corresponding to the diffraction pattern of an aperture. Additional results were obtained when turbules were given sinusoidal velocity components in the transverse directions. The measured and simulated signals were similar but the variations were faster in the measured signal than in the simulation. Subsequent to the presentation of this paper, I obtained the original data of the experiment. A phase-sensitive demodulation data analysis algorithm was applied. The phase so obtained could be followed through each 360° anomaly and the phase function, when fitted together, formed a continuous plot. The frequency of the phase-sensitive demodulation was then varied to achieve a minimum phase excursion during the 1-min data interval. The best value for minimum phase excursion was 500.08 Hz rather than the nominal 500 Hz first assumed. This result indicated (but did not prove) that the frozen turbulence hypothesis assumed in the simulation was appropriate. When I removed what appeared to be an anomalous peak in the experimental spectrum, the measured spectral width was some two to four times greater than the simulated signal spectral width. Additional results were calculated for the maximum reasonable transverse velocity functions applied to the turbules. The resulting spectrum did not vary enough to give any indication that transverse motion causes the measured spectral broadening. An adequate explanation of this broadening did not appear until later [23]. In the meantime, the failure of the model to show the correct broadening indicated that it was unlikely that resort to wave-propagation codes would resolve the issue. The use of ray theory for propagation calculations continued.

20. Auvermann, H. J., and G. H. Goedecke, "Acoustic scattering into shadow zones from atmospheric turbulence," *Proc. 4th Annual Ground Target Modeling and Validation Conference*, August 1993, Michigan Technological University, Houghton, MI, pp 327–336 (proceedings: B179603, paper: A381269).**

¹ Havelock, D. I., M. R. Stinson, and G. A. Daigle, "Phase and amplitude fluctuations in a refractive shadow," *J. Acoust. Soc. Am.* **92** (4), pt. 2, 1992.

This paper presents the reported evidence for turbulence scattering into shadow zones. The evidence for anisotropic scattering was then presented [1,5]. The idea behind an augmented version of the widely used fast field program (FFP) was then described. The new code is called the Acoustic Multistream Propagation Program (AMPP) [31]. The purpose of the new code was to incorporate anisotropy into the existing structure of FFP. Some preliminary results from AMPP are shown.

21. Auvermann, H. J., G. H. Goedecke, and M. D. DeAntonio, "Conclusions pertinent to acoustical scattering by atmospheric turbulence using a turbulence ensemble model," *Proc. 6th International Symposium on Long Range Sound Propagation*, 12 to 14 June 1994, Ottawa, Canada, pp 357-370 (A290920).**

This paper presented a summary of developments and conclusions reached in other papers. Also presented was a plot of the field from an anisotropic scatterer (represented as a dipole) obtained with the AMPP code [33].

22. Auvermann, H. J., "Comparison of coherent summation to incoherent summation of acoustic signals scattered from turbulence," *Proc. 7th International Symposium on Long Range Sound Propagation*, 24 to 26 July 1996, Ecully, France, pp 161-173 (A382049).**

In this paper, a carefully structured TEM was prepared with the use of the correct scattering patterns [5], the proper number concentrations [15], and the appropriate scattering volumes [13]. Coherent summation of the scattered signals was compared to incoherent summation for an ensemble flow time of 100 s. The coherent summation indeed showed greater variation and bandwidth than the incoherent summation. However, the variation was less than that exhibited by experimental results [19]. The conclusion was inescapable that something was missing from the TEM. The missing element of the TEM turned out to be the variation of the Doppler effect within the scattering volume when viewed in an experimental scenario. The items in the next section show how the Doppler effect was included.

6. Scattering From Moving Ensembles

Although the idea of the Doppler effect was advanced early in the development of TEM, the scenario without it was modeled intentionally because of the complications involved in its inclusion. The first scenarios modeled were similar to tactical ones with distances of thousands of meters. When experimental data became available for scattering into wind-induced shadow zones, scenarios were changed to those with distances of hundreds of meters extent typical of the experiments reported. Theory had indicated that scattering from turbules could cause great detector signal variations [19], but accumulating experience with relevant ensembles and scattering volumes indicated that the variations in simulations was not enough [22]. Inclusion of Doppler effects was therefore considered for an experimental scenario, one reason being that at larger distances Doppler could cause a frequency shift but not a broadening. A rough calculation revealed that as the turbule moved through the scattering volume, the frequency would vary enough to account for the experimental broadening. Items in this section report the development of this idea.

23. Auvermann, H. J. and G. H. Goedecke, "Influence of the Doppler effect on the bandwidth of acoustical signals scattered from atmospheric turbulence," *Proc. 8th International Symposium on Long Range Sound Propagation*, 9 to 11 September, 1998, Pennsylvania State University, PA, pp 375-388 (A382047).**

The detected signal scattered from moving turbules in an experimental scenario is calculated with the use of the time delay method for tracking the phase. A single turbule moving along a single path showed a broadening commensurate with measurements. Multiple turbules of the same size spaced along the same path are accurately simulated by phase delays of the components of the detected signal spectrum. The combined spectrum for five turbules exhibits the random-like behavior of the measured spectrum. A spectrum plot of three different turbule sizes and the experimental spectrum together show that the simulation broadening brackets the measured broadening.

24. Wood, Roy C., "Sound Scattering in a Moving Turbulent Atmosphere," Ph.D. dissertation, New Mexico State University, Las Cruces, NM, May 1999.*

In his dissertation, Wood develops expressions for the change of acoustic scattering cross section in a stratified atmosphere and compares results with results of two other investigations. The fluid equations from which the acoustic wave equation is derived are transformed to a moving frame and shown to be the same. The scattering properties of individual eddies is presented and then generalized to multiple eddies. Detector signals are written down including the retarding effects introduced by the moving scatterers. Simplification of the expressions is shown for small wind-to-sound speed ratios.

A computer code is developed with the use of the exact results of the theory, a time shift algorithm is developed that greatly reduces the calculation time, and a comprehensive set of results from the computer code is presented.

25. Goedecke, G. H., R. C. Wood, H. J. Auvermann, V. E. Ostashev, and Chueh Ting, "Spectral broadening of sound scattered by advecting atmospheric turbulence," *J. Acoust. Soc. Am.* **109** (5), pt 1, May 2001, pp 1923-1934.

This article gives an expanded view of the physical mechanism by which the Doppler effect broadens a single-frequency source tone when the scatterers move with a steady wind through an experimental region where scatterer heights are not vanishingly small with respect to the source-detector distance. Derivation of the scattering equations for the moving medium obtained by a Galilean coordinate transformation is then effected in much the same way as above [24] and below [27]. Results presented are much the same in the three publications.

26. Goedecke, G. H. and H. J. Auvermann, "Doppler broadening of sound scattered by advecting atmospheric turbulence," invited seminar, National Oceanic and Atmospheric Administration, Environmental Technology Laboratory, Boulder, CO, 15 September 1999 [No written record].

This seminar was presented at ETL to those scientists most familiar with turbulence and turbulence scattering who wished to be informed of current results that could be obtained by the use of models of isolated inhomogeneities (as TEM does). It was recognized by Dr. Tatarskii that the overall method is the same as the conventional method. The difference lies in the order of the summation (or integration) in the derivation chain. In the TEM derivation, the Fourier transform (integration) applied to turbules comes before the summation over scattering centers. A seminar attendee made the interesting comment that the method of representing turbulence as isolated inhomogeneities might be useful in turbulence research as a way to handle closure in large eddy simulations.

27. Goedecke, G. H. "Turbule Model of Turbulence Research. Doppler Broadening of Acoustic Waves Scattered by Turbulence Flowing With a Horizontal Wind," Contract No. DAAHO4-96-C-0086, TCN 97051, U. S. Army Research Office, P. O. Box 122, Research Triangle Park, NC, 25 November 1999 (see [29]).

This contract final report contains material covered in [24] and [25]. It also contains a listing of the FORTRAN code entitled SLOW EDDY, which is the program developed by Wood. Unfortunately, reports for these kinds of contracts are not usually published for general distribution.

28. Goedecke, G. H., R. C. Wood, H. J. Auvermann, and V. E. Ostashev, "Spectral broadening of sound scattered by atmospheric turbulence," paper presented at the 138th meeting of the Acoustical Society of America, 1 to 5 November 1999, Columbus, OH, *J. Acoust. Soc. Am.* **106** (4), pt. 2, October 1999 [abstract only], p 2144.

This paper briefly covers the material in [25]. Extensions of the model for describing anisotropic and intermittent atmospheric turbulence are suggested.

29. Goedecke, G. H., R. C. Wood, and H. J. Auvermann, "Doppler broadening of acoustic waves scattered by turbulence flowing with a horizontal wind," U. S. Army Research Laboratory, ARL-TR-2131, July 2000 (A380303).**

This ARL technical report is the same as [27] with a few minor editorial changes. In addition, flow diagrams have been substituted for the code listing.

7. Using Propagation Models With Turbulence Ensembles

As pointed out in [19], ray theory has continued as the propagation model for simulation of detector signals in experimental scenarios. In the meantime, work has been initiated in the incorporation of TEM into wave-propagation models. This section lists items associated with the progress in this area. With the mechanism behind the spectral broadening encountered in experiments apparently identified [23], work on the incorporation of TEM into the widely used propagation models assumes an added importance. See section 8 for a discussion of future efforts toward this incorporation.

30. Noble, John M., and Harry J. Auvermann, "The Effects of Large and Small Scale Turbulence on Sound Propagation in the Atmosphere," ARL-TR-565, March 1995, U. S. Army Research Laboratory, (A293651).**

This report discusses current and past turbulence models used to treat the effect of small- and large-scale turbulence on atmospheric acoustic propagation. Two of the effects are the scattering of sound by small-scale atmospheric turbulence and fluctuation of the speed of sound gradients by the passage of large-scale atmospheric turbulence. Until recently, most work in turbulence effects on acoustics has concentrated on the small-scale turbulence regime of the inertial subrange of the Kolmogorov spectrum. Earlier small-scale turbulence models were based on the statistical work of Tatarskii [1]. Current turbulence models focus more on the structural nature of the turbulence because the statistical approach does not account for all the turbulence effects being measured during acoustic propagation experiments. The large-scale turbulence problem cannot be managed adequately with a statistical approach because of the difficulty in accumulating sufficient data from large-scale scenarios.

31. Auvermann, H. J., R. L. Reynolds, and D. M. Brown, "Development of a Multistream Acoustic Propagation Model Including Scattering by Turbulence," U. S. Army Research Laboratory, ARL-TR-528, June 1995 (A296565).**

This report describes the basic structure of the AMPP (defined in [18]) that includes scattering by turbulence in the wave-propagation code known as the FFP (defined in [20]). AMPP has the capability to calculate and archive detected acoustic field data from multiple sources. This capability of AMPP is created by surrounding FFP by routines for keeping track of the characteristics and locations of the different sources. Scatterers are considered both detectors and sources. The detected signals at scatter locations are recorded in one pass through FFP. These detected signals are used to simulate an appropriate source for a second pass through FFP. Some of the data generated by FFP for signals deep in a shadow zone are questionable. It may be necessary to go to higher precision because AMPP uses FFP for calculations for which it was not intended. An improved AMPP is reported in [33]. One

conclusion of the work reported here is that the FFP version in use did not have the precision necessary for accurately modeling shadow-zone fields at tactical distances.

32. Marlin, D. H., "Acoustic Propagation Through Turbulence: The Turbulence Ensemble Model and the Green's Function Parabolic Equation," Ph.D. dissertation, New Mexico State University, Las Cruces, NM, April 1996.*

Marlin notes that TEM does not model the effects of refraction due to sound-speed gradients and that the Green's function parabolic equation (GFPE) does not ordinarily model turbulence. Marlin introduces turbulent scattering as a distribution of secondary sources, using direction- and beamwidth-dependent Gaussian starting fields. An energy balance problem results from the three-dimensional nature of the turbulent scattered fields vs. the two-dimensional nature of the GFPE. This is treated by the technique of range-averaging the scattered energy. The model uses interesting methods of averaging over turbulence distributions that result in reduced computational time. Use of the windowed Fourier transform² is an important innovation. Both of these concepts may be useful in extending TEM to more efficient handling of small turbulences.

33. Kotiaho, Markku P., "Improvements to the Acoustic Multistream Propagation Program," U. S. Army Research Laboratory, ARL-CR-209, February 1996 (A305926).**

This report recounts how an iteration error in the original code [31] was corrected. It also details how a new FFP version was created that would allow coherent summation of waves from multiple scatterers. Although the computational accuracy was great enough to handle interference effects caused by superposition of a multiplicity of sinusoids, the range-increment variable chosen by the standard FFP version was not fine enough for the AMPP application. The new version chooses this variable to be a fraction of the wavelength. The plot mentioned above [21], which shows the field from a dipole scatterer, served to confirm that codes such as FFP would give field results in both amplitude and phase accurate enough to make superposition feasible. It is possible that range increments of a fraction of a wavelength might help correct the apparent limitation of the FFP code at the tactical distances mentioned above [31].

² Chui, C. K., *An Introduction to Wavelets*, Academic Press, New York, 1992.

8. Summary

Two issues are addressed in this summary. The first has to do with modeling acoustical signals in shadow zones from an amplitude standpoint now that a model of spectral broadening is in place. None of the investigations so far has attempted to calculate the absolute signal level so that the simulated signal may be compared to absolute signal level measured in an experiment. Fortunately, comparison of spectral broadening does not require an absolute match-up between the two. To the extent that absolute levels can be shown to be the same in a TEM simulation as in an experiment, this comparison will show the TEM spacing parameter (related to turbulence number concentration), the size-class separation parameter, and the scattering amplitudes to be correct in their combined effect. It is good to keep in mind that the ray theory calculations made to date with the use of TEM simplified the physical processes with at least three conditions: the frozen turbulence hypothesis, no ground reflections, and no bending of rays in a medium with sound-speed gradients. The latter two are addressed in current wave-propagation models such as the parabolic equation (PE) model and the FFP. The success of TEM in modeling spectral broadening indicates that the frozen turbulence hypothesis is adequate, but favorable results may come about for a different reason, such as, for example, the use of isotropic homogeneous turbulence.

Use of wave-propagation models introduced in the previous paragraph leads to the second subject of this summary. Spectral broadening modeling has required the interpretation of actions in a moving frame from measurements in an at-rest frame. It is not clear how this interpretation can be introduced into propagation models such as the PE or the FFP. It appears that modeling of short-distance experiments offers several dividend possibilities for the future. Limitations of these models to two dimensions and to isotropic sources are hurdles to be overcome. AMPP [31] contains a computationally intense solution in the use of a multipole expansion for anisotropic sources. A step toward a three-dimensional propagation model has been made but not reported. Currently, this exists as a FORTRAN code embodying an extension of FFP published a number of years ago.³ Approximate methods have been developed [24,32] for reducing the computation time associated with the huge number of small turbules.

³ Nijs, L., and C.P.A. Wapenaar, "The influence of wind and temperature gradients on sound propagation, calculated with the two-way wave equation," *J. Acoust. Soc. Am.* **87** (5), May 1990, pp 1987-1998.

Appendix

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13. ABSTRACT (Maximum 200 words) The objective of one portion of the Army Research Laboratory program on acoustic propagation on the battlefield is to develop an advanced method of accounting for the effects of anisotropic inhomogeneous turbulence. The approach chosen was to extend the idea of eddies under the assumption that the turbulence field is made up of a multiplicity of isolated eddies of different sizes. This method of describing turbulence is called the Turbule Ensemble Model (TEM). A turbule is defined to be a localized inhomogeneity of any type. The primary types are temperature and velocity inhomogeneities; the term turbule is an extension of the idea of an eddy, which is normally associated with a velocity disturbance. In the TEM, then, the turbulent region is populated with a collection of turbules of different sizes and types with the locations of the turbules chosen according to some rule. Since the program began in 1992, a number of publications have been generated that have dealt with the details of creating and using the TEM concept. This report contains information on these reports including author, title, where copies may be obtained, date, and a brief description.				
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